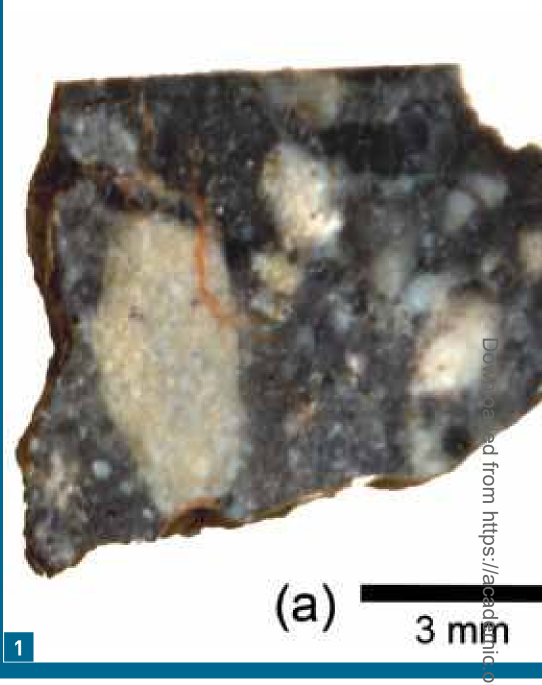
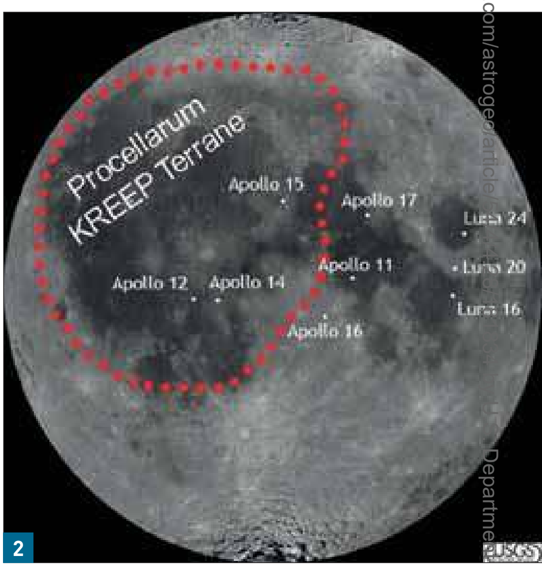
Lunar meteorites: new insights into the geological history of the Moon

Katherine H Joy and Tomoko Arai discuss the evidence from lunar meteorites about the shared history of Earth and the Moon.



1



2

The Moon is of scientific significance because it preserves a record of the early geological evolution of a terrestrial planet, inner solar system impact bombardment, and the solar and galactic environment throughout the last 4.5 billion years (NRC 2007, Crawford *et al.* 2012). It thus preserves evidence of the processes that affected the history of the Earth (NRC 2012).

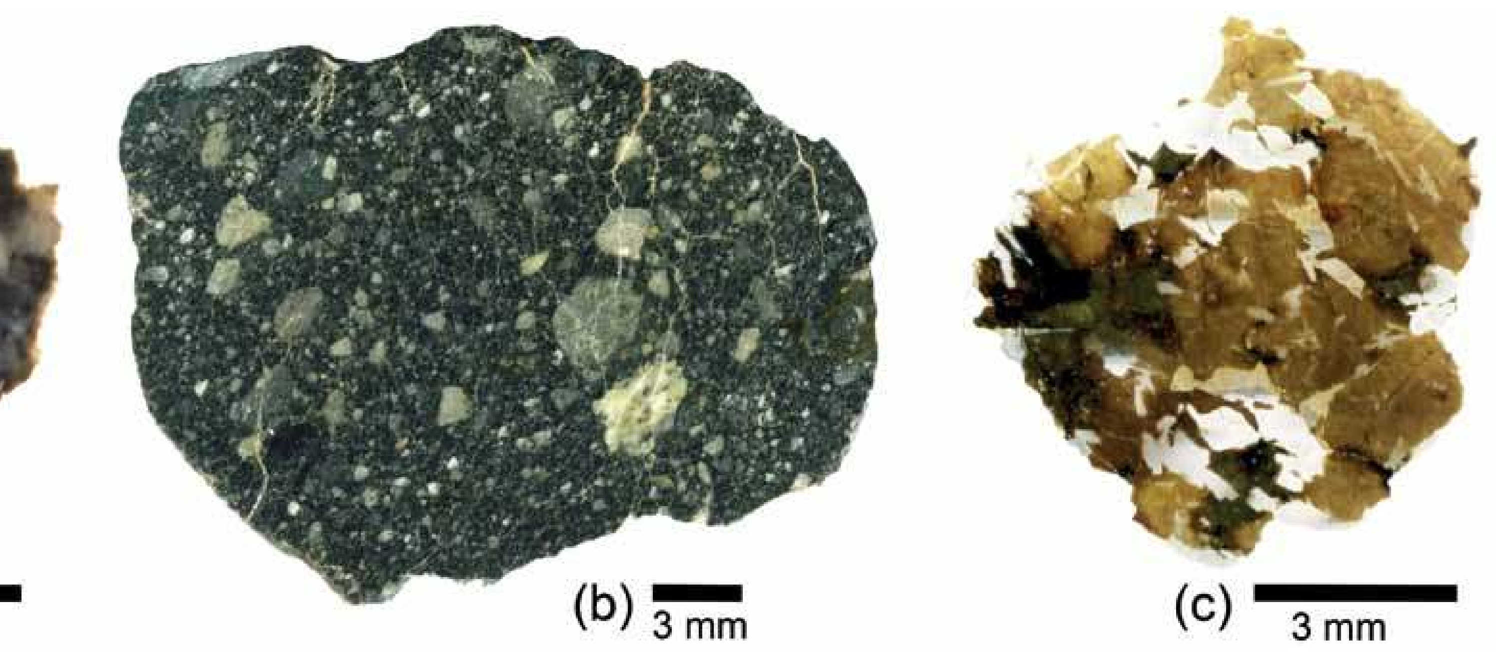
Manned and unmanned missions to the Moon returned ~382 kg of lunar rocks and soils (Vaniman *et al.* 1991) (see table 1 for a summary of lunar samples). These were collected by the Apollo missions from within and around equatorial latitudes on the central nearside of the Moon and by the Luna missions on the eastern nearside limb (figure 2). Remote-sensing data have subsequently shown that many of these landing sites actually sampled a geochemically unusual region, with enhanced concentrations of radioactive elements such as potassium and thorium. This region of the lunar nearside is known as the Procellarum KREEP Terrane (where KREEP is an acronym for potassium, rare earth elements and phosphorus-rich materials) (Jolliff *et al.* 2000) and this chemical signature is closely associated with impact ejecta from the large (~1200 km diameter), young (age estimates range from ~3.85 to 3.92 billion years old) Imbrium impact basin (figure 2). Therefore, although we have learnt a great amount about the Moon's past from studies of Apollo and Luna samples, interpretations have been made from a geographically restricted dataset within a region that does not necessarily best represent the Moon's global geological makeup.

Studies of Apollo and Luna samples suggest that, after the Moon formed at about 4.5 billion years ago, it was encased by a global magma ocean. The magma ocean slowly cooled and the Moon differentiated with a small dense core, an inner mantle made of Mg- and Fe-rich silicate minerals, and an outer feldspathic crust formed from silicate minerals rich in Ca and Al (see Shearer *et al.* 2006 and references therein for a detailed review). This "primary" crust makes up much of the white highland areas of the Moon. When the lunar highland crust had formed, the lunar interior was still hot and partially melted. These melts were intruded into the crust and formed magmatic "secondary" crustal rocks known as the high-magnesian suite and the high-alkali suite. The whole of the Moon was resurfaced by impacting asteroids and comets that formed large basins >300 km in diameter and smaller craters. Impact bombardment was high before ~3.7 billion years ago (Ga) when the lunar basins were formed. The duration and magnitude of this basin-forming epoch is debated: Apollo samples often have ages of 3.9 to 3.8 Ga (figure 3), suggesting an enhanced period of bombardment at this time often called the "lunar cataclysm" (Stöffler *et al.* 2006). After 3.8 Ga, volcanism was the dominate crust-forming process when mare basalts were erupted onto the surface as lava flows infilling many of the older impact basins: much of the lunar nearside is covered by these dark mare basalts, although only a few basalts outcrop on the farside (figure 2: note that mare basalt surface exposure constitutes only about 15% of the global lunar surface).

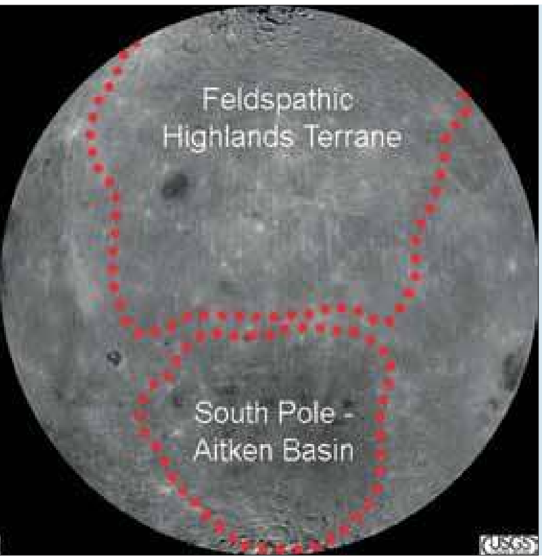
Lunar meteorites

Lunar meteorites (figure 1) are fragments of rock that were thrown off the Moon when it was struck by an impacting body, and then entered an Earth-crossing orbit. These rocks survived entry through Earth's atmosphere in a fireball to land on Earth as meteorites. To date, no-one has witnessed a lunar meteorite fireball fall event. All lunar meteorites are collected as finds in hot and cold desert environments where they have been preserved by low levels of precipitation and excess terrestrial weathering and are relatively easy to identify from the local terrestrial environment (for example, sitting on ice or a sandy desert with few terrestrial rocks).

Most lunar meteorites have been found in Antarctica, Oman and in the deserts of North West Africa, with a few from deserts in Australia and Botswana. The first lunar meteorites, Yamato-791197 and Yamato-793169, were collected in Antarctica in 1979 by the Japanese meteorite-hunting programme, although the first to be extensively studied as of lunar origin was Allan Hills (ALHA) 81005, collected by the US meteorite-hunting team in Antarctica in January 1982. Meteorites are named after the closest named geographic feature or town, with many Antarctic finds named



1: (a) Scanned thick section of feldspathic regolith breccia lunar meteorite Dar al Gani (DaG) 400 (Joy *et al.* 2010). Many small rock fragments (clasts) of impact melt breccias and anorthositic lithologies are consolidated together in a fine grained matrix.
(b) Scanned thick section of mingled breccia NWA 4472 where a range of basalt and impact melt clasts are consolidated in a dark matrix (Joy *et al.* 2011).
(c) Scanned thin section of crystalline basaltic meteorite Miller Range (MIL) 05035,34 (Joy *et al.* 2008). The meteorite has a very low-Ti bulk composition and is KREEP-poor compared with most Apollo and Luna mare basalts.



2: Location of the Apollo and Luna sample-return landing sites on the central nearside of the Moon. Also shown are the main lunar geochemical crustal terranes as defined by Jolliff *et al.* (2000). Overlain on a USGS Clementine mission albedo map of the Moon.

after the Allan Hills.

To date, there have been ~177 individual (named) lunar meteorite stones collected on Earth. Randy Korotev's excellent resource at http://meteorites.wustl.edu/lunar provides the most up-to-date list of lunar meteorites. Collectively this represents about 61 kg of lunar material, ~16% of the total mass returned by the Apollo and Luna missions. Some of these individual stones can be grouped through compositional, mineralogical or isotopic similarities and it is thought that they originate from ~85 separate fireball entry events. Some of these different Earth-arrival events may have actually been from the same ejection episode, and just arrived at different times and/or different places to the Earth (i.e. Arai and Warren 1999), so we probably have lunar meteorite material from at most 85 lunar-source impact craters and possibly from as few as 50 (Basilevsky *et al.* 2010).

Radiogenic isotope studies indicate that the majority of these lunar meteorites left the Moon in the past 10 million years and all of them in the past 20 million years (Korotev 2005). They are derived from relatively shallow depths of a few cm to tens of metres within the lunar surface (Lorenzetti *et al.* 2005), and probably were launched from small impact craters only a few kilometres or less in diameter (Warren 1994, Head *et al.* 2002, Basilevsky *et al.* 2010). We do not know the precise provenance on the lunar surface from where these meteorites originate, except ones with outstanding compositions that enable us to suggest their source crater (Gnos *et al.* 2004, Arai *et al.* 2010), but it is thought that they represent a random sampling of the lunar surface with some coming from the nearside and others from the polar regions or the farside (Korotev 2005). This, then, is their key scientific importance: in contrast to the Apollo and Luna samples, lunar meteorites represent global geological sampling of the Moon. As a result, studies of these samples have broadened our understanding of the Moon's geological diversity and have helped to advance lunar science by challenging the paradigms and hypothesis developed from studies of Apollo and Luna samples.

Studies of lunar meteorites have brought unique insights to the Moon in time and space, helping us to a better understanding of its global diversity and history. Recent key discoveries are presented here.

Compositional diversity

The lunar surface has been mixed (gardened) by impact collisions and is covered by a heterogeneous covering known as the lunar regolith which is a metre to a kilometre thick. The regolith is composed of a range of individual rock fragments varying in size from large boulders down to fine dust, and is constantly being formed and destroyed by impacting micrometeorites and larger colliding bodies. The layer is, thus, a key

Table 1: Description of key lunar lithologies

lithology	explanation	importance for studying lunar history
anorthosite (e.g. ferroan anorthosite suite)	rock dominated by the Ca-Al-silicate mineral plagioclase feldspar	typically very old rock that formed early in the Moon's history as part of the primary crust
high-magnesian suite	rocks that contain magnesian mafic minerals (pyroxene, olivine)	formed between 3.9 and 4.5 Ga in intrusive magmatic events
high-alkali suite	rare compositionally evolved rocks such as granite	formed between 3.9 and 4.5 Ga in intrusive magmatic events
KREEP-rich rocks	rocks with large amounts of radioactive elements potassium, rare earth elements and phosphous (KREEP)	related to late-stage differentiation products; likely associated with material in the Procellarum KREEP Terrane
mare basalt	rocks that contain a mixture of feldspar and mafic minerals	formed in eruptive volcanic events between ~4.35 and 1 Ga; mare basalts are dark coloured that flooded large basins on the lunar nearside
impact melt rock or impact breccia	remelted rock or complex breccia (small pieces of rock fused together by heating from impact events)	rock formed in an impact cratering or basin-forming event; the ages of these samples provide insights to the impact bombardment history of the Moon
regolith	soil that is formed by impact gardening and overturning	provides insight on interaction between Moon and space environment (e.g. impact processes, solar wind, galactic environment)
regolith breccia	soil that was fused back together into a rock with angular rock and mineral fragments	time capsules of ancient lunar soil that reveal Moon–space interactions in the past

boundary layer between the Moon and the surrounding space environment (Lucey *et al.* 2006).

Rock and mineral fragments within lunar meteorite regolith breccias have revealed new types of lunar lithologies, and the existence of minerals previously unknown to science. Such examples include a rock found by Gross and Treiman (2011) in lunar meteorite ALHA 81005 that is rich in the mineral spinel. This sample has been linked to recent remote-sensing observations of the mineral spinel present in unusually high volumes at the lunar surface (Pieters *et al.* 2011), and is shedding new light on magmatic processes in the lunar crust. Anand *et al.* (2004) discovered a new type of iron silicide mineral hapkeite (Fe_2Si) in lunar meteorite Dhofar 280, revealing the complexity of space weathering processes that exist within the lunar regolith.

Understanding the global morphological, mineralogical and chemical diversity of the Moon's surface is, thus, a key goal of many robotic lunar exploration missions. Many of these satellites carry experiments that require ground calibration to validate their data products. Typically the spatial resolution of these instruments are a few tens to hundreds of kilometres (i.e. X-ray and gamma-ray datasets), down to hundreds of metres per pixel (i.e. VIS-IR optical datasets), and many of these experiments have traditionally relied on the bulk composition/mineral spectral reflectance of the Apollo and Luna landing sites as a ground truth calibration (notably the Apollo 16 landing site as it has a less varied soil composition/mineral makeup compared to the others). However, as discussed above, many of these missions landed in chemically anomalous regions of the Moon; the composition of regolith breccia lunar meteorites has been used to calibrate remote-sensing geochemical datasets, providing a more accurate global perspective of the chemical diversity of the lunar surface (Warren 2005, Prettyman *et al.* 2006). Additionally, new instruments, such as the visible–near-infrared spectrometer on the Japanese Kaguya mission, have performed very high spatial-resolution mapping (20 m per pixel) to allow investigation of the mineralogy and chemical composition of local outcrops of crustal bedrocks and basalt flows at the metre scale (e.g. Ohtake *et al.* 2009). Interpretation of reflectance spectra for such localized target sites is necessitating the development of a new calibration dataset that uses information from crystalline rock fragments in lunar meteorites (e.g. Issacson *et al.* 2012, Arai *et al.* 2013).

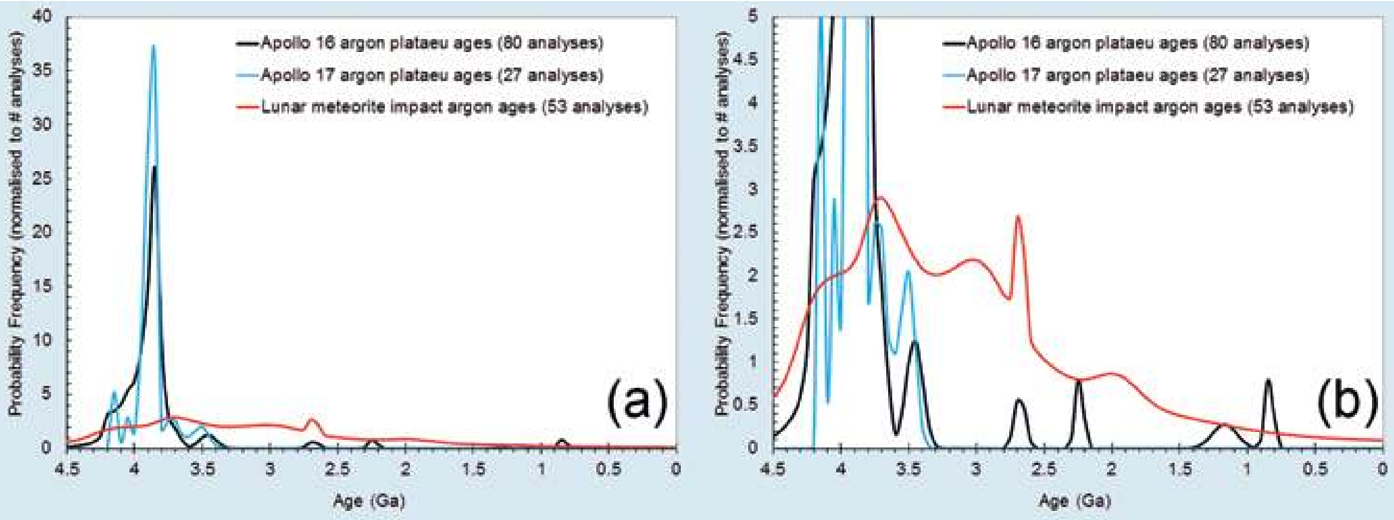
Formation of the primary crust

Feldspathic lunar meteorites (e.g. see figure 1a) have provided the first samples from the Feldspathic Highlands Terrane on the farside of the Moon (figure 2), offering new perspectives on the compositional diversity of the lunar primary crust (e.g. Palme *et al.* 1991, Korotev *et al.* 2003, 2009, Takeda *et al.* 2006), and the history of its formation (e.g. see review by Arai *et al.* 2008).

Recent examination of the compositional diversity of fragments of anorthositic material in feldspathic lunar meteorites (Takeda *et al.* 2006, Nyquist *et al.* 2010, Gross *et al.* 2012) further indicate that it is possible that the crust may not have formed in a simplistic single magma-ocean flotation event, and that more complex geological processes – multiple magma oceans, serial magmatism, differentiated impact melt sheets? – could be responsible for its formation and, thus, compositional heterogeneity. This debate is controversial because of the small sample sizes of rock fragments in lunar meteorite (see Warren 2012), but as additional samples are investigated with innovative geochemical and isotopic techniques over the next few years, together with studies of high-spatial-resolution remote-sensing data, their findings about the nature of the formation of the primary lunar crust could prove paradigm-shifting for ideas about planetary crust formation.

Mantle melting

Every new lunar basaltic meteorite that is petrologically, chronologically and isotopically



3: Timing of impact events as recorded by argon isotopes in Apollo 16 (black curve) and 17 (blue curve) and lunar meteorites (red curve). (a) Full *y*-axis scale and (b) limited *y*-axis scale showing details of the lunar meteorite dataset. To calculate these curves, the age and error were combined in bins of 0.5 Gyr (500 Myr), which is representative of the average error in $^{40}\text{Ar}/^{39}\text{Ar}$ age determination for the Apollo 16 samples. The normalized Gaussian curve calculated for each age bin (age column) was obtained by taking into consideration the width of the Gaussian curve calculated and the measured uncertainties. Each column was added and the result normalized to the total of all analyses per sample. Argon plateau data for Apollo 16 and 17 samples from supplementary dataset of Shuster *et al.* (2010) (see details for S2 and references therein) with additional data from Borchardt *et al.* (1986). Individual impact melt clasts and bulk rock (MacAlpine Hills 88105, Dar al Gani 400, Dar al Gani 262, Queen Alexandra Range 93069, Dhofar 026, 280 and 303) impact melt lunar meteorites taken from data compiled by Fernandes *et al.* (2013) with additional argon data from Yamato-86032 (Nyquist *et al.* 2006), Sayh al Uhaymir 169 (Gnos *et al.* 2004), North West Africa 482 (Daubar *et al.* 2002) and Dhofar 489 (Takeda *et al.* 2006).

characterized provides new insights to secular mantle-melting events, the role of impacts and KREEP in facilitating mantle melting, and heat flow in the lunar interior.

Mare basalts sampled by the Apollo and Luna missions are typically bimodal in composition between high-Ti (typically >10 wt% TiO_2 at Apollo 11 and 17) and low-Ti (1–6 wt% TiO_2 at Apollo 12 and 15) types (figure 4). However, basaltic lunar meteorites (figure 1c) are compositionally more diverse than Apollo and Luna samples, with many very-low-Ti (VLT: <1 wt% TiO_2) and rare intermediate TiO_2 (6–10 wt% TiO_2) hand specimens and small rock fragments (e.g. Robinson *et al.* 2012). These basalts also have different trace-element concentrations to the Apollo and Lunar samples (figure 5), offering new insights to the heterogeneity of the lunar mantle in regions both inside and outside of the nearside Procellarum KREEP Terrane.

Fragments of mare basalts are found in both feldspathic lunar meteorites and in mixed feldspathic–mare lunar meteorites (sometimes called mingled breccias: figure 1b). The presence of these basaltic fragments has been used to suggest that mare basalts may be more common in the lunar highlands than is witnessed in their current day surface expression (e.g. Terada *et al.* 2007, Arai *et al.* 2010, Basilevsky *et al.* 2010). Such deposits (known as cryptomaria) may have been covered up by the impact ejecta of younger impact basins, or may never have been erupted through the thick lunar crust at all, becoming retarded or trapped within the crust as intrusive equivalents (Head and Wilson 1992). Thus, these basaltic fragments demonstrate the possibly widespread distribution of mare basaltic volcanism and magmatism across the Moon.

Basaltic lunar meteorites have also provided new insights about the temporal history of mare basalt eruption. Apollo mare basalts were typically erupted between 3.2 and 3.8 Ga, where the older basalts had higher Ti content than the younger low-Ti basalts (figure 4). In contrast, basaltic lunar meteorites represent both the youngest 2.93 Ga (North West Africa 032: Borg *et al.* 2009) and the oldest 4.35 Ga (Kalahari 009: Terada *et al.* 2007) sampled mare basalt lava flows. The lunar meteorites show no relationship between age and bulk Ti-composition (figure 4), suggesting that the Apollo mare basalt dataset age–Ti correlation was an artefact of site sampling, and that secular melting in the lunar mantle is not coupled to the Ti-chemistry of the mare basalt source regions.

Bombardment history

A few lunar meteorite stones, and many individual rock fragments within brecciated samples (e.g. figure 3a and 3b) were formed in impact cratering episodes. Radiometric age-dating of these types of samples reveal the timing of impacts on the Moon (e.g. Cohen *et al.* 2000, 2005, Nyquist *et al.* 2006 and see figure 3 for summary). Lunar meteorite impact ages provide a vital insight (Taylor 1991) to studying the lunar cratering record in regions distal to the Imbrium basin-forming event, which likely dominate and bias the Apollo 16 and 17 record (figure 2 and figure 3). The number of lunar meteorite impact events (melts and reset sample ages) investigated is currently rather small (~50 to 60 data points: figure 3), but they suggest a relatively enhanced period of bombardment from ~4.2 Ga with a peak at ~3.7 Ga, and then declining events through the rest of the Late Imbrian into the Eratosthenian at ~2.5 Ga, whereafter the number of recorded events rapidly declines (figure 3b).

Taken together, these lunar meteorite age data show no large spikes prior to 4.2 Ga that would be consistent with ancient widespread basin formation caused by early solar system accretionary debris (Cohen *et al.* 2000). Instead, like the Apollo 16 and 17 samples (figure 3), they show an enhanced late bombardment episode (peaking at ~3.7 Ga). However, this epoch appears to have a longer duration than witnessed by the Apollo samples (figure 3). This could be taken to suggest global bombardment was sustained from 4.2 Ga until ~2.5 Ga. However, <3.7 Ga impacts in lunar meteorites cannot record basin-forming events as no basins (>300 km) were formed after this time. Thus, some of the longer duration enhanced bombardment records in lunar meteorites may reflect smaller and/or more localized impact cratering episodes (Chapman *et al.* 2007). It is, therefore, possible the Apollo and lunar meteorite impact records are both potentially complicated by their own sampling biases, although collecting additional melt ages will help further probe this archive and resolve the number and timing of global lunar impacts, which is critical to addressing the temporal history of impact bombardment in the inner solar system.

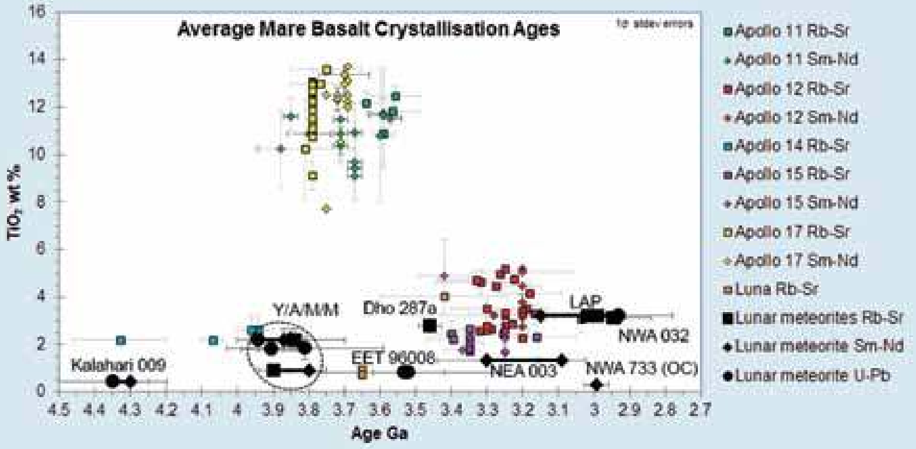
Future perspectives

The number of lunar meteorites is growing every year with privately funded searches of terrestrial hot desert, and government-supported Antarctic meteorite-hunting programmes. These important samples provide us with geological insights to previously unvisited regions of the Moon. Laboratory chemical, mineralogical, isotopic and chronological analysis of these samples has revealed important similarities and differences to samples in the Apollo and Luna sample collection.

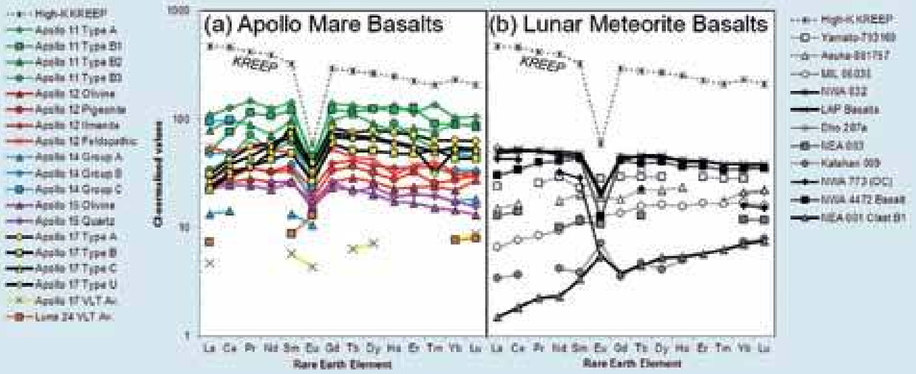
Lunar meteorites are, thus, shedding new light on lunar crustal, magmatic and impact history, and are helping us to test and constrain key models of the Moon's geological evolution. ●

Katherine H Joy, School of Earth, Atmospheric and Environmental Sciences, University of Manchester, UK (katherine.joy@manchester.ac.uk) and Tomoko Arai, Planetary Exploration Research Center (PERC), Chiba Institute of Technology, Narashino, Japan.

Acknowledgments. We are grateful to the Antarctic Search for Meteorites (ANSMET) programme that gave us the opportunity to discuss this topic at great length during many tent days in the 2012–2013 season at Szabo Bluff. Thank you to Randy Korotev, Clive Neal, Kevin Righter and Chuck Meyer for the excellent lunar resources and databases they have generously provided to the lunar community. KHJ acknowledges Leverhulme Trust grant 2011-569 and would like to thank Prof. Ian Crawford for his support and many informative discussions about lunar meteorites.



4: Comparison of mare basalt crystallization age and bulk TiO_2 chemistry. Apollo chemistry data are plotted as averages of different studies (data taken from Clive Neal's mare basalt database and references therein), and compared to age data from different radiometric systems (data taken from Clive Neal's age summary database). Lunar meteorite age and chemistry data taken from many literature sources including that compiled in NASA's Lunar Meteorite Compendium (Kevin Righter). Thick black lines connecting meteorites denote where two different ages using different methods have been derived for the same meteorite. The Y/A/M/M group of lunar meteorites are likely sourced from the same crater (Joy *et al.* 2008, Arai *et al.* 2010).



5: Differences in rare earth element (REE) chemistry between (a) Apollo basalts (average lava flows calculated from data in Clive Neal's mare basalt database) and (b) lunar meteorites (data from that compiled in the Lunar Meteorite Compendium; with additional data from Joy *et al.* 2011, Snape *et al.* 2011). Data have been normalized to CI chondrites and the composition of lunar high-K KREEP is provided in both plots for context. The shape of the REE profiles and Eu-anomalies are different between lava flows sampled by Apollo and lunar meteorites, suggesting origin from a wide range of mantle sources.

References

Anand M *et al.* 2004 *PNAS* **101** 6847–6851.
Arai T and Warren P H 1999 *Meteoritics & Planet. Sci.* **34** 209–234.
Arai T *et al.* 2008 *Earth Planets Space* **60** 433–444.
Arai T *et al* 2010 *Geochim. Cosmochim. Acta* **74** 2231–2248.
Arai *et al.* 2013 *Lunar and Planetary Science* **XXXXII** abstract #1016.
Basilevsky *et al.* 2010 *Planet. Space Sci.* **58** 1900–1905.
Borchardt R *et al.* 1986 *J. Geophys. Res.* **91** E43–E54.
Borg L E *et al.* 2009 *Geochim. Cosmochim. Acta* **73** 3963–3980.
Chapman C R *et al.* 2007 *Icarus* **189** 233–245.
Cohen B A *et al.* 2000 *Science* **290** 1754–1756.
Cohen B A *et al.* 2005 *Meteoritics & Planet. Sci.* **40** 755–777.
Crawford I A *et al.* 2012 *Planet. Space Sci.* **74** 3–14.
Daubar I J *et al.* 2002 *Meteoritics & Planet. Sci.* **37** 1797–1813.
Fernandes V A *et al.* 2013 *Meteoritics & Planet. Sci.* **48** 241–269.
Gnos E *et al.* 2004 *Science* **305** 657–659.
Gross J and Treiman A H 2011 *J. Geophys. Res.* **116** E10009 9 doi:10.1029/2011JE003858.
Gross J *et al.* 2012 *LPS XLIII* abstract #2306.
Head J W III and Wilson L 1992 *Geochim. Cosmochim. Acta* **56** 2155–2175.
Head J W III *et al.* 2002 *Science* **298** 1752–1756.
Isaacson P J *et al.* 2010 *Lunar and Planetary Science XLI* abstract #1927.
Jolliff B L *et al.* 2000 *J. Geophys. Res.* **105** 4197–4216.
Joy K H *et al.* 2008 *Geochim. Cosmochim. Acta* **72** 3822–3844.
Joy K H *et al.* 2010 *Meteoritics & Planet. Sci.* **45** 917–946.
Joy K H *et al.* 2011 *Geochim. Cosmochim. Acta* **75** 2420–2452.
Korotev R L 2005 *Chemie der Erde* **65** 297–346.
Korotev R L *et al.* 2003 *Geochim. Cosmochim. Acta.* **67** 4895–4923.
Korotev R L *et al.* 2009 *Meteoritics & Planet. Sci.* **44** 1287–1322.
Lorenzetti S *et al.* 2005 *Meteoritics & Planet. Sci.* **40** 315–327.
Lucey P *et al.* 2006 *Rev. Mineral. Geochem.* **60** 83–219.
NRC 2007 *The Scientific Context for the Exploration of the Moon* ISBN 0309109205.
NRC 2012 *Committee on New Research Opportunities in the Earth Sciences at the National Science Foundation* (National Research Council) ISBN 9780309219242 p117.
Nyquist L *et al.* 2006 *Geochim. Cosmochim. Acta* **70** 5990–6015.
Nyquist L *et al.* 2010 *Lunar and Planetary Science XLI* abstract #1383.
Ohtake M *et al.* 2009 *Nature* **461** 236–240.
Palme H *et al.* 1991 *Geochim. Cosmochim. Acta* **55** 3105–3122.
Pieters C M *et al.* 2011 *J. Geophys. Res.: Planets* E00G08 doi:10.1029/2010JE003727.
Prettyman T H *et al.* 2006 *J. Geophys. Res.: Planets* 111 E12007 doi:10.1029/2005JE002656.
Robinson K L *et al.* 2012 *Meteoritics & Planet. Sci.* **47** 387–399.
Shuster D L *et al.* 2010 *Earth and Planetary Science Letters* **290** 155–165.
Shearer C *et al.* 2006 *New Views of the Moon Rev. Mineral. Geochem.* **60** 365–518.
Stöffler D *et al.* 2006 *New Views of the Moon Rev. Mineral. Geochem.* **60** 519–596.
Snape J *et al.* 2011 *Meteoritics & Planet. Sci.* **46** 1288–1312.
Taylor G J 1991 *Geochim. Cosmochim. Acta* **55:11** 3031–3036.
Takeda H *et al.* 2006 *Earth Planet. Sci. Lett.* **247** 171–184.
Terada K *et al.* 2007 *Nature* **450** 849–853.
Vaniman D *et al.* 1991 Chapter 2 *Lunar Sourcebook: A User's Guide to the Moon* ISBN 0521334446.
Warren P H 1994 *Icarus* **111** 338–363.
Warren P H 2005 *Meteoritics & Planet. Sci.* **40** 335–511.
Warren P H 2012 *Second Conference on the Lunar Highlands Crust 2012* abstract #9034.